A RISK ASSESSMENT FOR HYDROCARBON-CONTAMINATED SOIL AT A WELL SITE IN ALBERTA, CANADA

by

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LIST OF ABBREVIATIONS

Abbreviation	Full Terminology
SSRA	Site-Specific Risk Assessment
AST	Above Ground Storage Tank
AER	Alberta Energy Regulator
AEP	Alberta Environment and Parks
EPEA	Alberta Environmental Protection and Enhancement Act
APEC	Areas of Potential Environmental Concern
bbl	Barrel
B	Benzene
CCME	Canadian Council of Ministers of the Environment
CAD	Canadian Dollars
cm	centimeters
CSM	Conceptual Site Model
COPC	Contaminants of Potential Concern
DUA	Domestic Use Aquifer
EC	Electrical Conductivity
ESA	Environmental Site Assessment
E	Ethylbenzene
EPC	Exposure Point Concentrations
FWAL	Freshwater Aquatic Life
GOA	Government of Alberta

HQ	Hazard Quotient
HC	Health Canada
K	hydraulic conductivity
F1-F4	Hydrocarbon Fractions F1-F4
ILCR	Incremental Lifetime Cancer Risk
IUR	Inhalation Unit Risk
km	kilometers
m	meters
mbgs	meters below ground surface
m/s	meters per second
MDL	Method Detection Limits
mg/L	Milligrams per Liter
OWA	Orphan Well Association
PBO	Parliamentary Budget Office
PHCs	Petroleum Hydrocarbons
PAHs	Polycyclic Aromatic Hydrocarbons
ROPCs	Receptor of Potential Concern
RAP	Remedial Action Plan
SAR	Sodium Absorption Ratio
SRA	Surface Rights Act
TC	Tolerable Concentration
T	Toluene

TDS	Total Dissolved Solids
TRVs	Toxicity Reference Values
UST	Underground Storage Tank
USEPA	United States Environmental Protection Agency
X	Xylene

ABSTRACT

In Alberta, Canada, there are lots of former oil and gas well sites which have pollutants. Thus, there are a growing number of oil and gas well sites requiring remediation to remove pollutants such as benzene. Management of these sites, as dictated by provincial regulation, can be achieved through Tier 1, Tier 2 or exposure controls. Tier 1 guidelines are generic and are designed to be protective under a range of conditions. The Tier 2 option allows for site-specific factors to be incorporated into guideline adjustments. However, it is not well known how much Tier 2 reduces risks and cost expenditures. An oil and gas well in Alberta provided a study site to evaluate whether remediating to Tier 2 guidelines was effective in reducing the human health risks and project expenditures. Therefore, I compared the human health risks through screening post-remediation soil-exposure concentrations to update the exposure, toxicity/effects assessments and risk characterizations. I completed this by using a three-phase partition model to convert soil concentrations into soil vapour concentrations. Soil vapour concentrations were then used to calculate indoor air concentrations and finally to a incremental lifetime cancer risk (ILCR). I found that remediation to Tier 2 guidelines eliminated 75% of contaminants of potential concern (COPCs). I also found there was a reduction in the remaining COPC benzene to below the in surface and subsurface soils. I used soil borehole and confirmatory lab analysis to estimate soil volumes to remediate to Tier 1. This estimated Tier 1 volume was compared to the known volumes excavated during the 2023 remedial excavation. Volumes were translated into project costs by using the unit rate in Canadian dollars (CAD). I found there was a 44% reduction costs related to earthworks through the remediation to Tier 2 guidelines. Overall, this means the Tier 2 pathway was effective at reducing human health risk and while reducing project costs.

INTRODUCTION

Oil and gas pollution framework in Alberta

In Alberta, Canada, the polluter-pays system is used for the oil and gas liabilities management framework (Alberta Energy and Minerals, 2024). Currently in Alberta, there are approximately 468,000 oil and gas wells in the province (AER, 2024). There are active (33.5%), inactive (16.8%), abandoned (19.6%) and reclaimed (29.7%) well sites (AER, 2024). Except for the reclaimed wells, this represents the estimated financial environmental liability for cleanup costs, which currently totals 33 billion dollars Canadian (CAD) (AER, 2024). The estimated liability is calculated by using Directive 011, which provides industry parameters and regional abandonment, and reclamation costs used in calculating liability (AER, 2024). However actual liability in Alberta may be 263% greater (88 billion CAD) than Directive 011 estimates, due to inaccurate information (Weber, 2024). With volume and evaluation of risks in mind, it is important for companies to manage remediation and reclamation costs. A potential scientific pathway to reduce costs is through Site-Specific Risk Assessments (SSRAs).

Environmental protection in Alberta is managed through application of the Environmental Protection and Enhancement Act (EPEA; Government of Alberta (GOA, 2006)), and the Water Act (GOA, 2000). The management of contaminated sites under this legislation provides three options: Tier 1, Tier 2 and Exposure Control (AEP, 2016) (AEP, 2022) (AEP, 2022). The Tier 1 approach involves the use of soil and groundwater remediation guidelines that are based on generic land- and water-use scenarios and exposure conditions. The Tier 2 approach allows for the modification of guidelines and SSRA to account for site specific conditions, which can be more or less sensitive than the generic scenarios used in the development of Tier 1

remediation guidelines. Exposure control involves the management of risks through physical barriers or administrative controls where required, based on the outcome of a risk assessment. Sites managed through exposure control are not eligible for a Remediation or Reclamation Certificate.

Contaminants commonly associated with oil and gas drilling and exploration sites include crude oil (Petroleum hydrocarbons (PHCs) (F1-F4), Polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene and xylene (BTEX), metals, produced water (salinity, sodicity, chlorides, sulphates, soluble inorganics), workover fluids (pH, salinity, methanol, glycol, brocides), chemical additives (pH, sodium, potassium, salinity, chloride, sulphates) and halogenated solvents (CCME, 2016). BTEX have demonstrated negative impacts on human health including effects on the nervous system, immune functions and reproductive health (Qin, et al., 2022).

Background

My study will focus on the Tier 2 reclamation approach for addressing contaminants of potential concern (COPCs) at a former wellsite in Alberta. I focus my analysis at Site A, a former sweet gas well located within an agricultural area within Alberta. A well is classified as a sweet gas well when there is an absence of hydrogen sulfide (H_2S). Site A was selected based on availability of historical site data at a location where a previous risk assessment and Tier 2 guideline adjustment were preformed. Site A consists of a gravel well pad, gravel berm and an access road. The well has been cut and capped. Former site infrastructure consisted of a dehydrator building, above ground storage tanks (ASTs), pipeline riser, and an underground storage tank (UST) that have all been removed. Previous work at the Site consisted of Phase 1

and 2 Environmental Site Assessments (ESAs), SSRA and remedial excavation. Phase 1 ESAs were completed in 2010 and updated in 2018. These assessments identified areas of potential environmental concern (APECs) and recorded historical site activities. Two Phase 2 ESAs were conducted at the Site in 2018 and 2021. The 2018 phase 2 data includes 22 boreholes locations of which three were installed as groundwater monitoring wells. The supplemental phase 2 conducted in 2021, comprised 3 boreholes and 18 hand auger locations with an additional groundwater monitoring well installed. In 2022, a SSRA was completed with the objective of evaluating human and ecological risks and developing a decision-making framework that would establish whether further assessment or remediation action was required. The SSRA determined for human health that a vapor inhalation pathway was operable, and the retained COPCs included BTX and F1 in surface soils and benzene in subsurface soils. A remedial excavation was initiated in the fall of 2023 to remove impacted material. A total of 29 soil samples were collected during the 2023 excavation. Excavated soils were transferred to a landfill for disposal.

Objectives

The objectives of my paper are to:

1. Conduct a follow-up human health risk assessment for soil COPCs (BTX and F1) at the Site following remediation activities (Chapter 1). The risk characterization will estimate the current extent of potential adverse effects on the Site.
2. Update the exposure and toxicity/effects assessments completed as part of the 2022 SSRA completed for COPCs (BTX and F1). This will allow for comparison between pre- and post-remediation soil COPCs (BTX and F1) risk at the Site (Chapter 1).

3. Complete a cost comparison between Tier 1 and Tier 2 guidelines for the purposes of remediating soil COPCs (BTX and F1) at the Site (Chapter 2).

CHAPTER 1: RISK ASSESSMENT

Background

The following chapter includes my overview of risk work completed to date. This work will be the basis for which post remedial exposure, toxicity/effects assessments and risk characterizations will be compared.

Regulatory and Risk Assessment Framework

Alberta Contaminated Site Policy Framework

Alberta Environment and Park's (AEP's) approach to managing contaminated sites is described in the Alberta Contaminated Sites Policy Framework (AEP, 2014). This framework applies when developing and assessing options for management of contaminated lands in Alberta and is established under the Alberta Environmental Protection and Enhancement Act (EPEA; Government of Alberta (GOA, 2000)). When a contaminant is released to, or found in the environment above natural background concentrations, the AEP framework for the management of contaminated sites requires that four activities occur: (1) source control, (2) ESA, (3) risk assessment and (4) contaminant management.

These activities are further defined below:

Source Control

A contaminant source is defined as anything that adds contaminant mass to an environmental media (such as soil, groundwater, soil vapour, surface water, air).

Environmental Site Assessment

The ESA must be extensive enough to review the Site information, summarize the Site conditions and prepare a Conceptual Site Model (CSM).

Risk Assessment

Risk assessment evaluates information on the potential toxic effects of contamination on human or ecological receptors in contact with contaminated soil, air, water and food through various exposure routes (pathways). Based on the results of the ESAs, a SSRA (including human health and ecological risk assessment) is considered the appropriate approach for the Site. A SSRA is a tool that systematically evaluates potential human health and ecological risks using realistic, site-specific assumptions. Once completed, the SSRA can be used to inform decisions about remediation and/or risk management requirements at a site.

SSRA comprises the following elements which summarize the process that I have undertaken in my analysis for the Site:

- Problem Formulation - summarizes background information, including details on land use, site setting and ecological characteristics of the Site, presents Site characterization data collected during field investigation activities, presents screening and selection of COPCs and Receptor of Potential Concern (ROPCs) species for quantitative analysis in the SSRA, summarizes fate and transport based on Site conditions, presents screening and selection of endpoints to evaluate risk, and includes further development of the CSM as warranted.

- Exposure Assessment - estimates the magnitude, frequency, and duration of exposure by the ROPCs to a stressor.
- Effects/Toxicity Assessment - evaluates the relationship between dose or degree of exposure to a substance and incidence, probability and/or severity of an organism's response.
- Risk Characterization - estimates the magnitude (and where possible, the probability) of adverse effects based on the information obtained from the exposure and effects/toxicity assessments, as well as evaluates the degree of uncertainty in the analysis and the link between risk characterization and risk management.

Guidance for completing a SSRA is available from AEP, GOA, Health Canada (HC), CCME, and Environment and Climate Change Canada (ECCC) as follows:

- Guidance for Selecting Toxicity Reference Values (TRVs) for Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guidelines (AEP, 2017).
- Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guidelines (AEPA, 2024) and (AEPA, 2024).
- Alberta's Remediation Certificate Program (AEP, 2019).
- GOA (2018) Environmental Quality Guidelines for Alberta Surface Waters (GOA, 2018).
- Health Canada (2021a) Federal Contaminated Site Risk Assessment in Canada: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 3.0 (HC, 2021).
- Health Canada (2021b) Federal Contaminated Site Risk Assessment in Canada: Toxicological Reference Values (TRVs), Version 3.0 (HC, 2021).

- Health Canada (2010) Federal Contaminated Site Risk Assessment in Canada, Part V: Guidance on Human Health Detailed Quantitative Risk Assessment for Chemicals (DQRACHEM) (HC, 2010).
- CCME (1999) Protocols for Deriving Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water) (CCME, 1999).
- CCME (2006) Protocol for Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006).
- CCME (2007) Protocol for the Derivation of Water Quality Guidelines for the Protection of Aquatic Life (CCME, 2007).
- CCME (2008) Canada-Wide Standard for Petroleum Hydrocarbons (PHC) in Soil: Scientific Rationale, Supporting Technical Document (CCME, 2008).
- CCME (2020) Ecological Risk Assessment Guidance Document (CCME, 2020).
- ECCC (2012) Federal Contaminated Sites Action Plan (FCSAP) Ecological Risk Assessment Guidance (ECCC, 2012).

If information was not available from the above documents, guidance from the United States Environmental Protection Agency (USEPA) was followed (USEPA, 1998).

Contaminant Management

Contaminant management refers to the actions of reducing risks to human or ecological ROPCs caused by residual contamination in a manner consistent with AEP's framework for the management of contaminated sites. If action is required to manage contamination, two options are available: 1) remediation and 2) exposure control. Remediation is the removal or treatment of residual contamination (AEPA, 2024).

If remediation is not technically or economically feasible, unacceptable risks caused by the residual contamination must be managed via exposure control methods (AEP, 2016).

Problem Formulation

A summary of the problem formulation completed as part of the 2022 SSRA is provided below.

Site Conditions

Site Description

The Site is in an agricultural area with numerous oil and gas operations. The sweet gas well was spudded in April 1989 and operated periodically until 2011 when it was abandoned. During operation, the Site infrastructure included a dehydrator building, ASTs, a pipeline riser and a UST. The UST was found to be leaking during a routine tank testing program after Site operations and ceased and was removed prior to 2017. Remediation did not occur during the UST removal. The well was cut and capped in 2017.

The Site before remediation comprised a bare gravel well pad with a gravel berm in the southeast corner and an access road. Other above and below ground infrastructure, except for the AST berm, was removed from the Site during the winter of 2018.

Land Use

The land use at the Site and surrounding areas is agricultural. Oil and gas operations are also present in the area.

Topography and Drainage

The Site is generally flat with localized areas of subsidence related to the removal of former infrastructure. A north-south drainage channel is located approximately 130 m east of the Site lease and bisects the Site access road. A river is the dominant regional drainage feature, located approximately 14 km east of the Site.

Surface Water Body

The nearest surface water bodies are a potential wetland located approximately 440 m northeast from the Site and a Creek located approximately 4 km NE from the Site.
One surface water user record was identified within a 1-km radius of the Site. The surface water license was issued for livestock watering.

Surficial Deposits

The main lithology at the Site is clay with varying minor silt and sand content extending to 8.9 meters below ground surface (mbgs). Occasional sandy, silt lenses were observed within the clay unit in the east-southeast area of the Site. The clay is overlain by approximately 15 cm to 30 cm of topsoil outside of the teardrop wellsite footprint, and up to 30 cm of gravelly material within the teardrop of the Site. The amount of gravelly material within the teardrop was variable due to disturbance during the infrastructure removal.

Bedrock Geology

The area is underlain by bedrock of the Cretaceous age. The Horseshoe Canyon Formation (Edmonton Group) is represented by grey, fine to very fine-grained, feldspathic sandstone interbedded with siltstone, bentonitic mudstone, carbonaceous mudstone,

concretionary sideritic layers and laterally continuous coal seams. A white, pedogenically altered sandstone and mudstone interval may be present (formerly assigned to the Whitemud Formation). The formation is classified as non-marine to locally marginal marine (AGS, 2013). Bedrock, characterized as weathered siltstone, was encountered at a depth of 8.9 mbgs at one borehole location (BH21-2). The depth of investigation at other locations was 6.0 mbgs or higher and bedrock was not encountered.

Hydrogeology

Groundwater flow, direction and velocity have not been defined at the Site given that only two monitoring wells on Site have consistently produced water. During the drilling programs, little indication of a productive shallow groundwater bearing zone was observed. Clay materials had damp/moist areas during intrusive investigations, but only three monitoring wells have produced water.

Hydraulic conductivity (K) testing at one monitoring well (MW21-01) within the shallow groundwater-bearing zone had a K value of 1×10^{-7} m/s. MW18-3A did not produce sufficient water to complete hydraulic conductivity testing suggesting a K value of $<10^{-7}$ m/s. Hydraulic conductivity testing from Shelby tube samples at 5.5 mbgs in MW21-1A and 9.5 mbgs at BH21-2 were 5.4×10^{-10} m/s and 8.3×10^{-10} m/s, respectively.
The SSRA assumed the shallow groundwater bearing zone is not a domestic use aquifer (DUA) based on the low productivity of installed monitoring wells and the K value below 10^{-6} m/s. A lower groundwater bearing zone was not discovered to the depth of investigation.

Water Wells

There is one water well record reported within 300 m of the Site and an additional water well located within 1 km of the Site. The water well within 300 m of the Site was drilled to 67 m for unknown purposes. The type of work was reported as a well inventory. The drilling report did not specify the well owner, date drilled, or lithology. The water well within 1 km is for industrial use.

Remediation and Reclamation History

A remedial excavation was completed in October of 2023 with reclamation activities completed in the fall of 2024.

Previous Investigations and Assessments

A Phase 1 ESA was conducted in 2010 to identify Areas APECs at the Site. In 2018, an updated Phase 1 ESA was conducted. The 2018 Phase 1 ESA confirmed the findings of the 2010 Phase 1 ESA and included additional details related to Site activities including: the contents of the tanks and historical well fracturing activities. Details of the Site decommissioning were also included in the update.

A Phase 2 ESA was completed in 2018 consisting of geophysical surveys, the advancement of 22 boreholes and the installation of three groundwater monitoring wells. Borehole and monitoring well locations were selected based on the results of the Phase 1 ESAs and the results of the geophysical surveys.

Groundwater monitoring began at the Site in October 2018; subsequent monitoring events were conducted in August 2019, November 2019, October 2021, August 2022, May 2023 and October 2023.

Limitations of Conceptual Site Model

Limitations on the extent of knowledge at the Site were identified, although they were not considered to materially affect the overall understanding of Site conditions. They are summarized below.

- Characterization of groundwater flow direction and velocity at the Site was limited in 2021 due to low productivity of existing monitoring wells. Fine-grained materials have been observed to a depth of approximately 8.9 mbgs, above the bedrock interface and the one measured K value (MW21-01) is 10^{-7} m/s. Collectively, these data generally suggest that contaminant transport in groundwater is of limited concern at the Site and that further assessment to evaluate groundwater is not warranted at this time.
- Concentrations of benzene, ethylbenzene, xylenes and PHC F1 exceed the guidelines protective of the DUA. The shallow groundwater bearing zone was excluded as a DUA based on a measured K value below 10^{-7} m/s at one monitoring well and low productivity at a second monitoring well.
- A deeper groundwater bearing zone was not identified to the depth investigated (10.2 mbgs). The Domenico and Robbins Transport Model with guidance from the Tier 1 and Tier 2 Remediation Guidelines (AEP, 2019) (AEP, 2019) was used to demonstrate that residual contamination in soils would not reach the bedrock interface and to confirm the exclusion of the DUA is protective of underlying groundwater as well.
- Delineation to Tier 2 Guidelines was achieved across the Site except at one location, BH18-8. BH18-8 was located at the center of the contaminant source and other samples have been vertically delineated nearby. Two other locations, BH18-16 and MW21-01,

had not been vertically delineated to Tier 1 guidelines; however, BH18-16 and MW21-01 were delineated to the Tier 2 guidelines. Vertical concentration profiles generally show a decreasing trend in concentrations.

Background Conditions

Groundwater

Three monitoring wells were installed on the Site outside the footprint of soil PHC impacts in 2018: two outside the Site operational area to the north (MW18-1A) and east (MW18-2A) and one near the Site access road (MW18-3A). One additional monitoring well was installed in 2021 (MW21-1A) beneath the PHC impacts in soils. Of the 2018 wells, only MW18-3A had sufficient groundwater for sampling. During the 2021 monitoring event, MW21-1A was sampled for a limited subset of parameters.

Results from MW18-3A samples indicate groundwater in this monitoring well is not impacted by PHCs, herbicides, methanol or chromium; these parameters were below method detection limits (MDLs) during historical sampling events. AEP Tier 1 guideline exceedances of salinity (electrical conductivity [EC], chloride, sodium), total dissolved solids (TDS), sulphate, nitrate and select metals (cadmium, copper, manganese, selenium, uranium) were measured in MW18-3A.

The elevated EC value measured at MW18-3A is generally attributable to elevated sulphate in groundwater. While groundwater flow direction has not been conclusively determined based on limited groundwater data, it appears groundwater flow has a northerly component. Furthermore, salinity and metals were generally below guidelines in soils; given they have also not been observed in soils with hydrocarbon impacts, it is unlikely they are present due

to Site activities. Collectively, these lines of evidence suggest the elevated parameters in MW18-3A are likely to be naturally occurring and therefore, have not been considered further at the Site.

In general, groundwater chemistry at MW18-3A suggests groundwater is unusable for use as a DUA or for other agricultural purposes (livestock watering, irrigation). High concentrations of sodium (above 200 mg/L) and sulphate (above 500 mg/L) are above guidelines for potable water and background water quality with an EC>2000 µS/cm and/or TDS>1300 mg/L is deemed "unusable" for agricultural use (GOA, 2018). Therefore, in addition to the exclusion of the DUA outlined above, use of groundwater for livestock watering and/or irrigation water is also excluded.

Areas of Potential Concern

Four APECs were identified that were considered as potential sources of impact at the Site (Figure 2):

- APEC 1: Well center;
- APEC 2: Dehydrator shack/pipeline;
- APEC 3: UST; and
- APEC 4: 400-barrel (bbl) AST within berm.

Contaminants of Potential Concern (COPCs)

A COPC is a substance which may pose a risk to the health of a receptor if exposure occurs. For the SSRA, only COPCs in soils were retained based on exclusion of the DUA, livestock watering and irrigation watering due to low hydraulic conductivity, low permeability material overlying bedrock and high naturally occurring EC, TDS and sulphate that would render the aquifer unsuitable for agricultural use.

Assessment Guidelines

The following guidelines were used as screening levels for the soils at the Site:

- The Alberta Tier 1 and Tier 2 Soil and Groundwater Remediation Guidelines were used as screening guidelines for the Site ((AEP, 2022) (AEP, 2019), respectively).
  - The soil quality guidelines for agricultural land use were applied based on current and future land use.
  - Fine-grained guidelines were applied based on measure particle size.
- Pathway exclusions and guideline adjustments included:
    - Subsurface soils were considered greater than 1.5 mbgs. For petroleum hydrocarbons (PHC) fractions (F) below 1.5 m, the AEP (AEP, 2019) subsoil guidelines were applied with direct soil contact and ingestion pathways excluded.
    - Guidelines protective of Freshwater Aquatic Life (FWAL) were not applied based on the distance to potential receiving bodies (440 m to the nearest potential surface water body).
    - Pathway guidelines for a DUA were excluded based on a lack of evidence that the shallow groundwater bearing zone underneath the Site can sustain yield and evidence that impacts will not reach a lower groundwater bearing zone.
    - Pathway guidelines for the irrigation water, livestock watering, and wildlife watering scenarios were excluded based on no impacts in groundwater and evidence that impacts will not reach an underlying DUA.

- Based on measured soluble salt concentrations in soil at the inferred background/unimpacted borehole locations, topsoil EC and sodium absorption ratio (SAR) were rated as “Good”, whereas subsoil EC and SAR ratings ranged from “Good” to “Fair”. Subsoil is defined within the guidelines as the B and C horizons whereas topsoil is defined as the surface A, L, F, H and O horizons or equivalent surface soil where those horizons are not present (AENV, 2001). Where topsoil was absent at the Site and there was no equivalent rooting zone, the subsoil guideline was applied to all soil material.

Soil Screening

The identification of COPCs was completed by comparing the maximum measured concentration of substances historically related to Site activities in soils against background levels and the screening level for that substance. If the maximum measured concentration was above background concentrations and the screening level, the substance was retained for further evaluation. Substances where concentrations were below the MDL in each environmental medium were not included in the screening tables.

Conceptual Site Model (CSM)

The CSM for the Site is presented below. Source – receptor – pathway linkages were identified for further assessment in the SSRA.

Fate and Transport

The following fate and transport mechanisms in consideration of human and ecological receptors reflect operable conditions at the Site:

- COPCs can migrate downwards/leach into groundwater because of surface water infiltration or through preferential pathways such as fractures. At the Site, shallow groundwater had not been impacted by PHCs, including those PHCs measured in soils within the shallow saturated zone. A fine-grained layer of low permeability materials to a depth of approximately 8.9 m was expected to minimize downward migration of hydrocarbon compounds in soils. Therefore, this was not considered a substantial transport mechanism at the Site and was not considered further.
- COPCs may volatilize and/or vaporize and generate soil vapor, potentially entering basements through foundation cracks or migrating through diffusive or advective flow to outdoor air. While there is currently no building on the Site, a building could be constructed in future (with the applicable set back distance from well center) and so this pathway was considered.
- COPCs in soils from exposed areas may be suspended as dust and deposited downwind from the source. Generally, impacts were not present in surficial materials (e.g., shallow impacts are present at a depth of 1.0 mbgs at the Site). Therefore, this is not considered a substantial transport mechanism at the Site and was not considered further.
- Surface water runoff may occur in areas lacking vegetation, leading to erosion of surface soils. Generally, impacts were not present in surficial materials (e.g., shallow impacts are present at a depth of 1.0 mbgs at the Site). Therefore, this was not considered a substantial transport mechanism at the Site and was not considered further.
- Concentrations of COPCs may decrease due to adsorption, dispersion and dilution during transport, biodegradation, abiotic processes and other mechanisms of natural attenuation.

Evidence supports that this was occurring at the Site based on reductions in hydrocarbon concentrations from 2018 to 2021.

Receptors of Potential Concern (ROPCs)

Human Receptors

Under an agricultural land use scenario, a farm resident is assumed to always be present anywhere on agricultural land (AEP, 2019). Farm residents typically evaluated include toddlers and adults that live and work on the Site.

Ecological Receptors

For agricultural land use scenarios, ecological receptors typically include primary producers (crops and wild species), soil invertebrates, livestock, wildlife, and FWAL. Receptors where concentrations of hydrocarbons exceeded guidelines, except for FWAL, were retained for the assessment. FWAL receptors were excluded since the distance to the nearest surface water body is greater than 300 m.

Exposure Pathways

The operable pathway for human health risk was determined to be indoor inhalation of vapors and the operable pathway for ecological risk was direct soil contact and wildlife soil and food ingestion. These pathways were deemed to be operable based on exceedances of the guidelines.

Management Limits and Risk Management

PHC F1 exceeded the management limits. For PHC F1, the basis of the management limit is the soil saturation concentration (Csat) which represents the concentration where free phase formation may concern. At the Site, PHC F1 concentrations exceed the management limits (based on Csat) indicating that free phase formation was a potential concern.

Management Goals

The management goal for the Site was to utilize risk assessment to minimize potential remedial volumes while affording protection to human and ecological receptors. As such, the conclusions of the SSRA were incorporated into the Remedial Action Plan (RAP) for the Site to optimize remedial volumes.

Exposure Assessment

Exposure Point Concentrations

The exposure point concentrations (EPCs) measured during the SSRA are summarized below in Table 1. These are values that represent the maximum values of COPCs at the Site prior to excavation.

Table 1. Exposure Point Concentrations at Site A prior to remedial excavation.

Contaminants of Potential Concern	**Exposure Point Concentration (mg/kg (Max Value))**
Surface Soils	
Benzene	32.8
Toluene	280
Xylenes	366

PHC F1	2660
Subsurface Soils	
Benzene	13.5

Human Indoor Air Inhalation

Indoor air exposure concentrations used the soil EPCs (Table 1) for the assessment of human health. A three-phase partition model (HC, 2010) was used to estimate soil vapour concentrations. Default attenuation and bioattenuation factors were applied to estimate indoor air concentrations from soil vapor sources within 30 cm of a foundation (AEP, 2019). The three phase partition model with attenuation and bioattenuation factors are discussed in greater detail in the methods section below.

Table 2. Calculated indoor air concentrations for Site A Contaminants of Potential Concern

Contaminants of Potential Concern	**Soil Exposure Point Concentration (mg/kg)**	**Estimated Soil Vapour Concentration (mg/m^3)**	**Estimated Indoor Air Concentration (mg/m^3)**
Surface Soils			
Benzene	32.8	1.1×10^4	11
Toluene	280	4.9×10^4	49
Xylenes	366	2.5×10^4	25

PHC F1	2660	1.1×10^5	110
Subsurface Soils			
Benzene	13.5	4.6×10^5	4.6

Toxicity/Effects Assessment

The toxicity/effects assessment used toxicity information from human and/or animal studies to identify potential health risks at a range of dose or concentration levels in exposed populations. The TRVs were identified in the Alberta Tier 1 Soil and Groundwater Remediation Guidelines (2019).

Quantification of Human Toxicity

For benzene, AEP provides a non-threshold (cancer) TRV (inhalation unit risk; IUR). For other COPCs, threshold (non-cancer) TRVs were available (tolerable concentration; TC). For PHC F1, a threshold TRV was derived using the AEP (2019) provided standard fractionation makeup of PHC F1 and TRVs for the individual PHC fractions. The TRVs utilized in the 2021 SSRA are summarized in Table 4.

Table 3. Inhalation Tolerable Concentrations (TC) and Inhalation Unit Risk (IUR) (AEP, 2019a).

COPC	TC (mg/m^3)	IUR (mg/m^3)
Benzene	-	0.0033
Toluene	3.8	-

Xylenes	0.18	-
Aliphatic C6-C8 (55%)	18.4	-
Aliphatic C>8-C10 (36%)	1.0	-
Aromatic C>8-C10 (9%)	0.2	-
PHC F1	10.5	-

Risk Characterization

The toxicity and effects assessments were used to calculate the extent of potential adverse effects in the risk characterization. Risks to receptors were characterized by using the exposure dose/ concentration evaluated against a guideline or TRV. The comparison of the Site concentrations against the target risk levels aids in identifying areas of the site that required remediation.

Risk Equations and Target Risk Levels

The information from the exposure and toxicity/effects assessments above were used to calculate potential risks to human and ecological receptors.

Human Health

The incremental lifetime cancer risk (ILCR) was estimated using the IUR (for benzene only). For the other COPCs, the non-carcinogenic risks (Hazard Quotient (HQs)) were estimated using the TC values in Table 3. Then HQs were added to get the Hazard Index, representing cumulative non-carcinogenic risk. For the SSRA, an ILCR level below 1 x 10^{-5} times the non-

threshold TRV was considered negligible or representative of *de minimis* cancer risk. For non-carcinogenic risk, a HQ/HI value less than 1.0 was considered negligible. The inhalation ILCR and inhalation HQ were elevated above the desired human health target risk levels (Table 4.). For benzene an inhalation ILCR 0.04 is elevated above the *de minimis* cancer risk of 0.000000033, while the HQ for the remain non-carcinogenic COPCs were > 1.0. The characterization of human health risks is summarized in Table 4.

Table 4. Human Health Risk Characterization of Contaminates of Potential Concern at Site A prior to remedial excavation

COPC	**EPC (mg/kg)**	**Inhalation Threshold TRV (mg/m^3)**	**Inhalation HQ**	**Non-threshold TRV $(mg/m^3)^{-1}$**	**Inhalation ILCR**
Surface Soil (0-1.5 mbgs)					
Benzene	11	**-**	**-**	**0.0033**	**0.04**
Toluene	49	3.8	**13**	-	-
Xylenes	25	0.18	**140**	**-**	**-**
PHC F1	110	10.5	**10**		
	Hazard Index (HI)		**163**		
Subsurface Soils (>1.5 mbgs)					
Benzene	4.6	-	-	0.0033	**0.02**

Tier 2

Tier 2 guidelines were used as screening levels to confirm that soil remediation had been completed. The applied Tier 2 values for COPCs at the Site are available in Tables 5 and 6.

Parameter	Maximum Concentration (2018-2021 Soils [mg\/kg])	Background Concentration (mg/kg)	Pathway Specific Guideline Values (mg/kg)							
			De minimus pathway-specific guideline	**Potable Water**	**Inhalation**	**Eco Soil Contact**	**Aquatic Life**	**Livestock**	**Wildlife**	**Management Limit**
Surface Soils (0-1.5 mbgs)										
Benzene	**32.8**	ND	0.33	0.046	0.33	60	7.9	0.2	18	-
Toluene	**280**	ND	110	0.52	1200	110	63,000	26	980	-
Xylenes	**366**	ND	65	0.99	140	65	NGR	160	2,600	-
PHC F1	**2660**	ND	210	1,100	610	210	30,000	6,600	11,000	800
Subsurface Soils (>1.5 mbgs)										
Benzene	**13.5**	ND	5.0	0.046	5.0	120	7.9	0.2	15	-

Table 5. Pathway specific guideline values for Contaminates of Potential Concern at Site A prior to remedial excavation.

Notes: Greyed out guideline values were excluded based on CSM; ND= non-detect; NGR= no guideline required; "-"= no guideline provided and **Red highlighted** concentrations indicate the concentration is above the acceptable limit.

After completing the remedial excavation, all impacts were remediated to below Tier 2 guidelines (Appendix A; Table 6). Of the COPCs identified in the site-specific risk assessment only benzene was detected in surface and subsoils, as toluene, xylenes and PHC F1 were below detection limits (BDL).

Table 6. Post remedial excavation contaminates of potential concern concentrations.

			Pathway Specific Guideline Values (mg/kg)							
Parameter	Maximum Concentration (2018-2023 Soils [mg\/kg])	Background Concentration (mg/kg)	*De minimus* pathway-specific guideline	**Potable Water**	**Inhalation**	**Eco Soil Contact**	**Aquatic Life**	**Livestock**	**Wildlife**	**Management Limit**
Surface Soils (0-1.5 mbgs)										
Benzene	**0.024**	ND	0.33	0.046	0.33	60	7.9	0.2	18	-
Toluene	**ND**	ND	110	0.52	1200	110	63,000	26	980	-
Xylenes	**ND**	ND	65	0.99	140	65	NGR	160	2,600	-
PHC F1	**ND**	ND	210	1,100	610	210	30,000	6,600	11,000	800
Subsurface Soils (>1.5 mbgs)										
Benzene	**1.53**	ND	5.0	0.046	5.0	120	7.9	0.2	15	-

Notes: Greyed out guideline values were excluded based on CSM; ND= non-detect; NGR= no guideline required; "-"= no guideline provided and **Green highlighted** concentrations indicate the concentration is above the acceptable limit.

Methods

Problem Formulation

My first step after remediation was to review the conclusions reached in the problem formulation developed as part of the SSRA. As the site conditions and potential receptors have remained unchanged these conclusions were retained for the purposes of this study. The SSRA determined that the inhalation pathway for humans was operable due to exceedances of the guidelines (Table 5). While all COPCs were remediated to below Tier 2 guidelines during the SSRA, my paper focuses on benzene for further evaluation to establish the current benzene risk for comparative purposes. Xylene and F1 will not be carried forward as concentrations were below detection limits (Table 6) and the toluene pathway was excluded as it was an ecological pathway. Since the finalization of the SSRA in 2022 there have been two updates to the Alberta Tier 1 and 2 Soil and Groundwater Remediation Guidelines (2022 and 2024). The finalized updates do not affect benzene guidelines (AEP 2024a/b).

Exposure Assessment

The second step in completing the human health risk assessment for the site post remediation was for me to complete an exposure assessment. The goal of the exposure assessment was to characterize the mechanisms by which receptors are exposed to the COPCs and to quantify the magnitude of those exposures (ECCC, 2012). The exposure assessment for the COPC benzene involved estimating the intake by receptors via the inhalation pathway. I estimated an exposure concentration in the relevant exposure media (soil).

Human Indoor Air Inhalation

Indoor air exposure via inhalation concentrations were calculated for the COPC benzene using the soil EPCs (Table 6). The EPCs values were the maximum concentration of benzene (mg/kg) in surface and subsurface soils remaining after screening the site soils data to remove excavated data (Table 6). The EPC for surface benzene was 0.024 mg/kg and the EPC for subsurface benzene was 1.53 mg/kg. A three-phase partition model (HC, 2010) was used to estimate soil vapor concentrations for surface and subsurface benzene.

Three-phase Partition Model for a Soil Contamination Source

If $Csoil < Csat,soil$ then

$$Csv = UCF2 * Csoil * H' * \frac{\rho b}{\theta w+(Koc*foc*pb)+(H'*\theta a)}$$

If $Csoil < Csat,soil$ then

$$Csv = Max\ [(UCF2 * Csoil * H' * \frac{\rho b}{\theta w+(Koc*foc*pb)+(H'*\theta a)}), (\frac{UCF1*MW*X*P}{R*T})]$$

$$Csat,soil = S * \frac{\theta w + (Koc * foc * \rho b) + (H\prime * \theta a)}{Pb}$$

where:

- Csoil = soil concentration;
- Csat,soil = soil saturation concentration;
- CSV = concentration in soil vapour (mg/m^3);
- UCF1 = unit conversion factor (1,000 mg/g);
- UCF2 = unit conversion factor (1,000 L/m^3);

- H' = Dimensionless Henry's Law Constant;
- ρb = dry bulk density (g/cm^3);
- θw = water filled porosity (unitless);
- θa = air filled porosity (unitless);
- Koc = organic carbon-water partitioning coefficient (mL/g);
- Foc = fraction organic carbon (foc);
- MW = molecular weight (g/mole);
- X = mole fraction (unitless);
- P = pure chemical vapour pressure (atm);
- R = Gas constant (m^3-atm/K-mole); and
- T = Absolute temperature (K, 273ºC).

A site-specific attenuation (1.0 x 10^{-5}; Appendix C) and bioattenuation (10) factors were applied to estimate the indoor air concentration from soil vapor sources within 30 cm of a foundation (AEP, 2022).

Estimation of Indoor Air Concentrations

$Cia = (CSV \times \alpha) / BAF$

where:

- *Cia* = concentration in indoor air (mg/m^3);
- CSV = concentration in soil vapor (mg/m^3);
- α = attenuation factor (unitless); and
- BAF = bioattenuation factor (unitless; applicable to hydrocarbons only).

Toxicity/ Effects Assessment

TRVs provided in AEP Tier 1 and 2 Soil and groundwater remediation guidelines (2024) were used to identify potential health risks at various dose and concentration levels of the COPC benzene. The IUR was updated in the Alberta Tier 1 and 2 Soil and Groundwater Remediation Guidelines update January 2023 (AEPA, 2024).

The IUR is based on the unit lifetime leukemia risk to the public (HC, 2021). The 0.0016 mg/m^3 in the HC guidelines is calculated from two studies identified by the Office of Environmental Health Hazard Assessment California Environmental Protection Agency (OEHHA), 2001). The IUR=[0.044 (parts per million $(ppm)^{-1}$ (Rinsky, et al., 1987) x 0.056 $(ppm)^{-1}$ (Hayes, et al., 1997)]$^{1/2}$=0.050 $(ppm)^{-1}$ or 0.016 (mg/m^3). The values come from chronic exposure to benzene for occupationally exposed workers (HC, 2013). There is a correlation with chronic exposure and the incidence of leukima (HC, 2013).

Risk Characterization

The risks to humans at the Site were calculated using values obtained in the exposure and toxicity/effect assessments. The relevant calculated values from the exposure assessment include the estimated soil vapour concentration (mg/m^3) and estimated indoor air concentration (mg/m^3) of benzene in surface and subsurface soils. The referenced IUR value from the toxicity effects assessment was also required. The IUR represents the TRV from Health Canada (HC) and represents the lifetime leukemia risk to the general population (AEPA 2024; HC 2021). Risks to humans were characterized using the estimated exposure concentration of the COPC benzene evaluated against the TRV value deemed protective of humans.

Human Health

Human Incremental Lifetime Cancer Risk (ILCR) Equation (Benzene)

$ILCR = (EC)(IUR_C)$

where:

- ILCR = incremental cancer risk (unitless);
- EC = exposure concentration in air (mg/m^3);
- IURc = inhalation unit risk $(mg/m^3)^{-1}$.

Results

Results for the three-phase partition model are available in Appendix A. The three-phase partition model was updated from the SSRA to account for the changes to the soil EPCs post remediation and well as additional site-specific data collected in 2023. The site-specific values entered into the calculation for Soil Vapor concentration included dry bulk density (1.88 g/cm^3), water filled porosity (0.269), air filled porosity (0.035), organic carbon-water partitioning coefficient (81 mL/g) and fraction organic carbon (0.021). The calculated indoor air concentrations of benzene were 0.00292 mg/m^3 and 0.0001 mg/m^3 (Table 7).

Table 7. Estimated Indoor Air Concentrations from Soil Exposure Point Concentrations.

Contaminants of Potential Concern	**Soil Exposure Point Concentration (mg/kg)**	**Estimated Soil Vapour Concentration (mg/m^3)**	**Attenuation Factor (AEP 2019b)**	**Bioattenuation Factor (AEP 2019b)**	**Estimated Indoor Air Concentration (mg/m^3)**
Benzene (Surface)	0.024	2.92	0.00001	10	0.00000292
Benzene (Subsurface)	1.53	186	0.00001	10	0.0001

The calculated ILCR for surface and sub-surface benzene was 0.000000004 and 0.000002 (Table 8).

Table 8. Estimated Indoor Air Concentrations from Soil EPCs

Contaminants of Potential Concern	Exposure Point Concentrations (mg/kg)	Non-threshold Toxicity Reference Values (mg/m^3)	Inhalation Incremental Lifetime Cancer Risk
Benzene (Surface)	0.00000292	0.016	0.000000004
Benzene (Subsurface)	0.0001	0.016	0.000002

Discussion

There are several lines of evidence that illustrate the remedial excavation has reduced the risks at the Site. Final confirmatory samples in the base and walls of the excavation met Tier 2 guidelines. Tier 2 guidelines are designed to provide human and environmental protection (AEPA 2024). The removal of impacted material surrounding the UST resulted in benzene being the only COPC from the 2021 SSRA and 2023 Tier 2 Guideline development to be retained for further evaluation. The updated soil EPCs for benzene resulted in the Inhalation ILCR being reduced in both the surface and subsurface to below the updated non-threshold TRV from 0.04 to 0.00000004 in surface soils and 0.02 and to 0.000002 in the subsurface soils. The Inhalation ILCRs calculated for both surface and subsurface were below the acceptable risk level of

0.000625, which is 10^{-5} the IUR of 0.016. According to Health Canada risks below 10^{-5} are considered negligible (HC, 2021). These significant changes are the result of using additional site-specific information, adjusting the attenuation factors, and reduction of soil EPCs.

CHAPTER 2: ALBERTA TIER 1 AND TIER 2 COST COMPARISON

Background

The completion of the SSRA allowed for the development of select Tier 2 Guidelines for the COPCs (BTX and PHC F1) in soil. Management of Site A under Tier 2 guidelines produces equivalent health and environmental protection as Tier 1 by integrating site-specific data into the creation of remediation guidelines (AEPA 2024a). Alberta Tier 1 guidelines are generally conservative, which protects human health and environment in such a way that their use can be applied across the most sites without conditions or restrictions (AEP 2024a). Sites remediated to Tier 2 guidelines qualify for regulatory closure. This feature of Tier 2 guidelines ensures the ability for Regulatory closure via a reclamation certificate. A reclamation certificate is a requirement to release operators from any surface leases. After securing subsurface rights operators are required to obtain a surface lease agreement (Environmental Law Centre, 2006). Surface lease agreements are a necessity for above ground infrastructure and is regulated in the Surface Rights Act (SRA) (POA, 2024). The SRA outlines compensation factors that are owed to the licensee (landowner) (POA, 2024). Compensation factors include entry fees, value of the land, loss of land and adverse effects (POA, 2024). The entry and annual compensation are negotiated between both parties. The annual compensation remains in effect until a remediation certificate is issued (POA, 2024). By using SSRAs and Tier 2 guidelines to achieve a reclamation certificate it ensures operators do not incur costs in perpetuity.

One of the stated goals of the SSRA was to optimize remedial volumes at Site A. The benefits of this strategy are that soil is an important resource and managing remedial volumes will reduce remedial and reclamation costs. As stated previously Tier 1 guidelines are more

restrictive than Tier 2 (Table 9). By using Tier 2 guidelines the quantity of soil requiring remediation should be reduced and diverted from the landfill. The Tier 2 process supports AER objectives to conserve and reclaim disturbed land, while not having a negative impact (AEPA, 2024).

Table 9. Tier 2 and Tier 1 guideline comparison at Site A.

Contaminants of Potential Concern	Tier 2 Site-Specific Guidelines (mg/kg)	Tier 1 Guidelines (mg/kg)
Surface Soils (0-1.5 mbgs)		
Benzene	0.33	0.046
Toluene	110	0.52
Ethylbenzene	120	0.073
Xylenes	65	0.99
Subsurface Soil (>1.5mbgs)		
Benzene	5.0	0.046
Toluene	1,200	0.52
Ethylbenzene	1,900	0.073
Xylenes	140	0.99
PHC F1	630	420
PHC F2	3,300	300

While the Site is currently under the care and responsibility of the operator, Alberta has seen an increase in the number of orphan oil and gas wells regionally. In 2022 the Parliamentary

Budget Office (PBO) of Canada released a report on the estimated cost of cleaning Canada's orphan oil and gas wells (Office of the Parlimentary Budget Officer, 2022). In the report, Alberta's orphan oil and gas wells had grown from 700 to > 8,600 wells (PBO, 2022). The PBO is responsible for supporting the parliamentary debate in federal government through economic and financial analysis. Currently in Alberta there are 7,395 wells designated as orphan (Orphan Well Association, 2024). A well is designated as orphan by the Orphan Well Association (OWA), when there is not a financially viable of responsible owner (OWA, 2024). The mandate of the OWA is "*to decommission Alberta's orphan oil and gas wells, pipelines and production facilities, and restore the land similar to its original state, all in a safe, principled and cost-efficient manner."*

The Site provides an excellent case study to evaluate the cost efficiencies of remediating to Tier 2 guidelines.

Methods

My first step in the comparison between Tier 1 and Tier 2 was to estimate the soil volume (m^3) that would require removal to meet Tier 1 guidelines for PHCs. I plotted the GPS coordinates of boreholes and confirmatory soil sample locations collected during ESAs and the remedial excavation in Google Earth Pro (Google Earth) (Figures 1-8). Locations having values exceeding Tier 1 guidelines were highlighted (Figure 4, 7 and 8). The proposed Tier 1 excavation horizontal boundary was delineated using the polygon tool in Google Earth (Figure 8). The produced polygon provided an estimated impacted area (m^2). The vertical delineation was calculated using borehole and confirmatory sample depth (m) information. Based on sample depths, un-impacted overburden depth was calculated by subtracting overburden depth (m) from

the total thickness (m). The remaining vertical depth (m) is the impacted soil thickness. Estimated unimpacted overburden and impacted volumes (m^3) could be calculated using the estimated impacted area (m^2) multiplied by the overburden or impacted thickness (m). Once volumes (m^3) of unimpacted overburden and impacted material were known. The difference was calculated by subtracting the known Tier 2 quantities calculated during the remedial excavation activities in 2023 from the estimated Tier 1 values. These difference between the known Tier 2 volumes and estimated Tier 1 can be translated into project costs in Canadian dollars (CAD) by using the 2023 sub-contractor unit rates quote. The unit rates provide costs/ volume (m^3) for site activities (Table 10). When the proposed scope of work for the 2023 remedial excavation was put out for proposal a description of the work was provided. The primary line-item activities related to remedial volumes were earthworks and trucking and disposal costs. The earthwork description of site work includes the excavation of PHC impacted soil and excavation of unimpacted overburden. The excavation of overburden and impacted material was completed utilizing a tracked excavator. Trucking and disposal costs include the transport of impacted material to the nearest approved Class 2 landfill. Class II landfills are non-hazardous waste landfills. Trucking services were provided by a third-party contractor utilizing various trucking platforms.

Table 11. Summary of 2023 Tier 2 Unit Rates

Activity	Unit Rate (CAD)
Excavate Impacts	8.90/m^3
Excavate Overburden	3.30/m^3
Transport and Disposal of Material	27.00/m^3

Results

During the 2023 Remedial Excavation to Tier 2 guidelines 1413 m^3 of impacted material was removed to the landfill and a total of 303 m^3 of overburden material was stripped and stockpiled at the Site (Table 11).

Table 11. Summary of 2023 Tier 2 Remedial Excavation volumes

Material Source	Material Destination	Volume (m^3)
Impacted	Landfill	1,413
Overburden	Remedial Excavation	303

Figures 1 through 8 were created to visually show the differences in locations and volumes based on guidelines exceedances at Site A (Figures 1-8). Based on the remaining PHCs elevated above Tier 1 guideline on-site the estimated area of the excavation calculated by Google Earth was 637 m^2 (Figure 8). Using sample depths, it can be assumed that the top 1 mbgs can be saved as clean overburden and utilized onsite (Appendix A). A conservative volume would include excavating material to 6 mbgs, as most of the impacted material is observed between 5.0-6.0 mbgs. The results of the calculation would give an estimated impacted volume of 3,185 m^3 and estimated overburden volume of 637 m^3 (Table 12).

Table 12. Summary of Estimated Tier 1 Remedial Excavation volumes

Material Source	Material Destination	Volume (m^3)
Impacted	Landfill	3,185
Clean overburden	Remedial Excavation	637

Translating these volumes into project costs for the core activities results in the increase of 64, 716 CAD for the Site (Table 13).

Table 13. Summary of estimated cost expenditures for calculated Tier 1 and know Tier Remedial Volumes

Activity	Tier 1 (m^3)	Unit/Rate (CAD/m^3)	Total (CAD)	Tier 2 (m^3)	Unit/Rate (CAD/m^3)	Total (CAD)	Difference (CAD)/ (% diff.)
Excavating Impacts	3,185	8.90	28,346	1,413	8.90	12,576	15,770 (% 44)
Excavating Overburden	637	3.30	2,102	303	3.30	1,000	1,102 (% 47)
Disposal	3,185	27.00	85,995	1,143	27.00	38,151	47,844 (% 44)
Total			**116,443**			**51,727**	**64,716 (44%)**

Discussion

When evaluating the cost comparison between Tier 1 and Tier 2 there is a 64,716 CAD difference. The difference translates to a 44% reduction in costs for the earthworks portion of the remediation. To put the total dollar value into context, the OWA in their 2023/2024 report placed had average cleanup cost of reclaiming a well at 27, 400 CAD (OWA, 2024). In the report the OWA also made note that the average remediation costs in 2023 do not necessary represent all

sites in the OWA portfolio or reflect industry averages (2024). These statements are supported by Yewchuck et al. (2023) who determined that the auditor general identified the current liabilities estimated by the AER to be 60 billion CAD, while holding approximately 295 million in security (Yewchuck, Fluker, & Olszynski, 2023). To further illustrate this, the unit cost to mobilize and demobilize equipment (Excavator) to carry out earthwork tasks involved in the remedial excavation was 8,950 CAD. The equipment mobilization would represent nearly a third of the OWA costs of reclaiming a well. These findings highlight the importance of the savings incurred via the SSRA and Tier 2 guideline development.

While the cost savings incurred via Tier 2 guidelines are significant, they also likely underrepresent total cost savings at the Site. Secondary costs related to volumes would include personnel costs, support trailer, backfill volumes and stand-by rates. These secondary costs are more difficult to evaluate.



Figure 1. Site Plan showing soil sample locations of the 2018 and 2021 environmental site assessments at Site A.



Figure 2. Tier 1 Petroleum Hydrocarbon (PHCs) Exceedances at Site A.



Figure 3. Tier 2 Petroleum Hydrocarbon (PHCs) Exceedances at Site A.

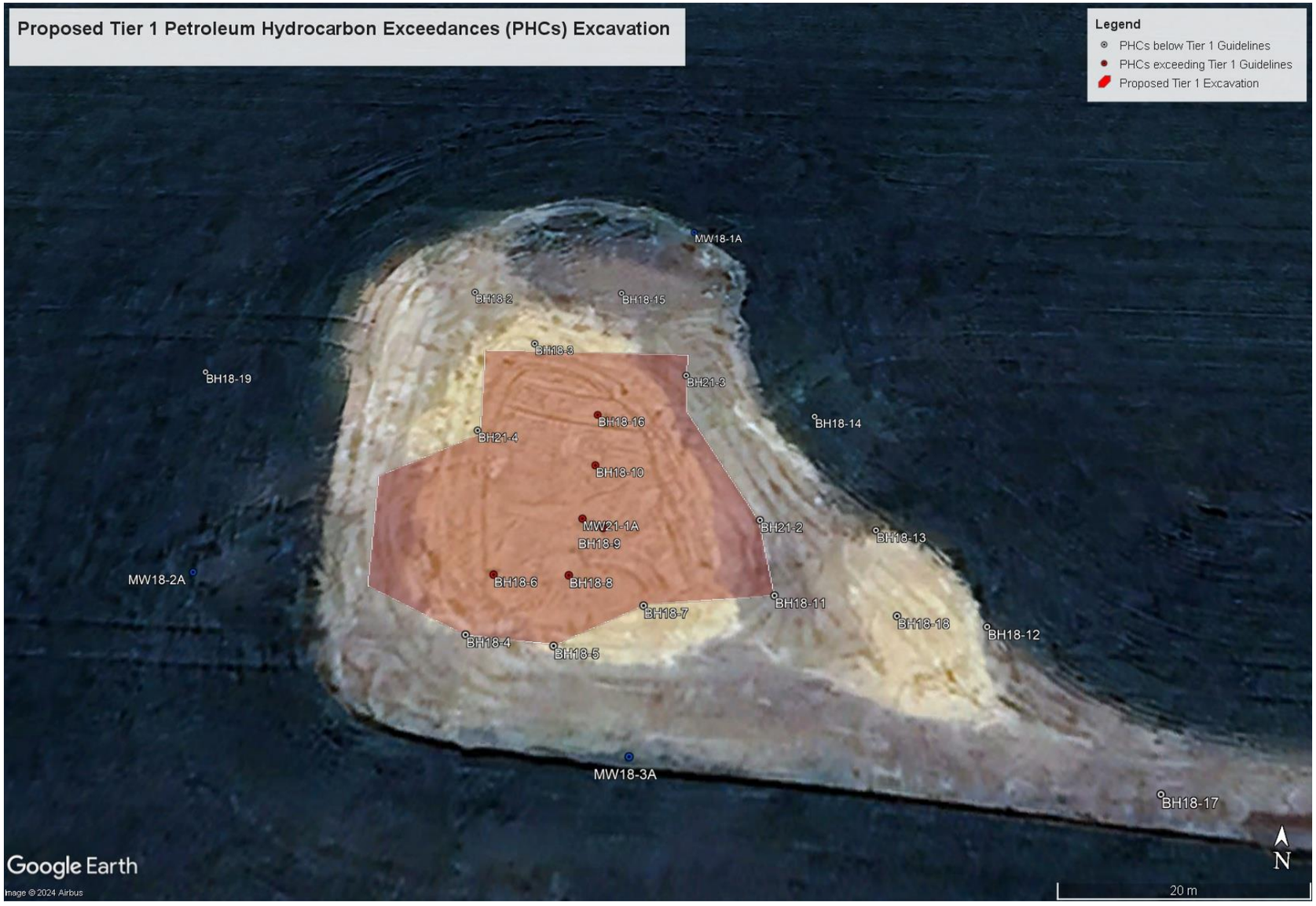


Figure 4. Estimated excavation boundary for Tier 1 PHCs guideline exceedances at Site A.



Figure 5. Estimated excavation boundary for Tier 2 PHCs guideline exceedances at Site A.

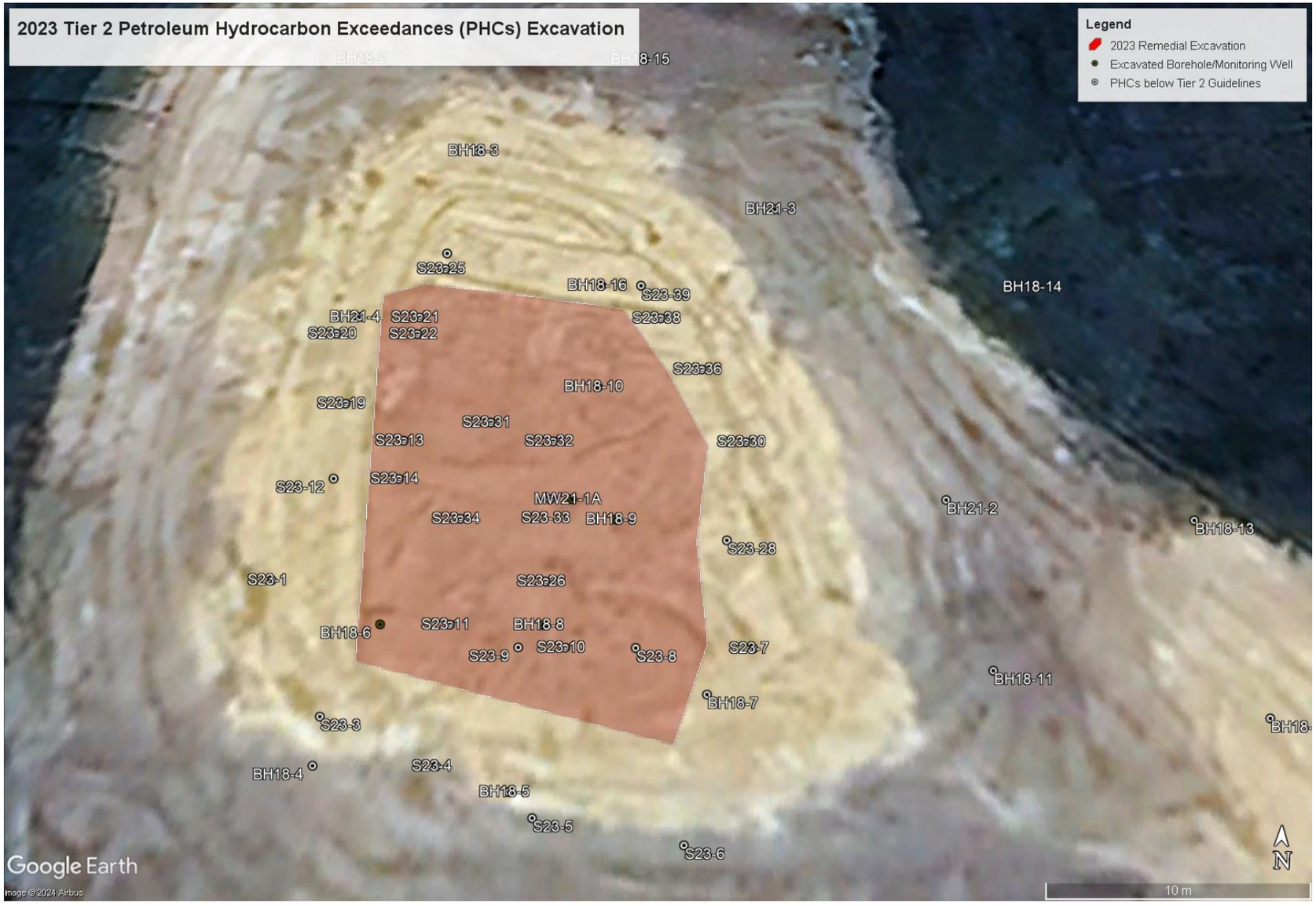


Figure 6. Final 2023 Tier 2 Petroleum Hydrocarbon Excavation boundary.

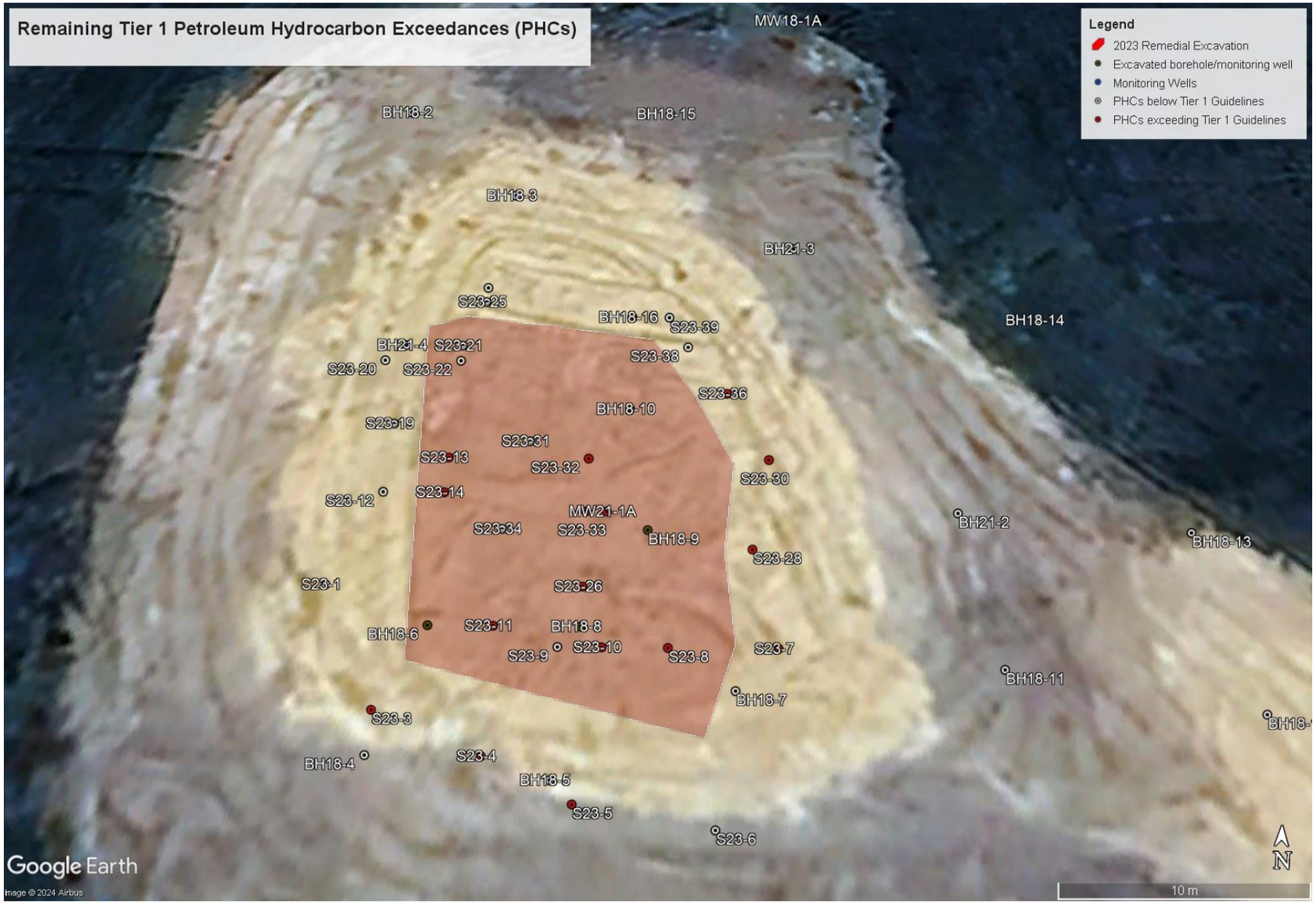


Figure 7. Remaining Tier 1 Petroleum Hydrocarbon Exceedances at Site A.

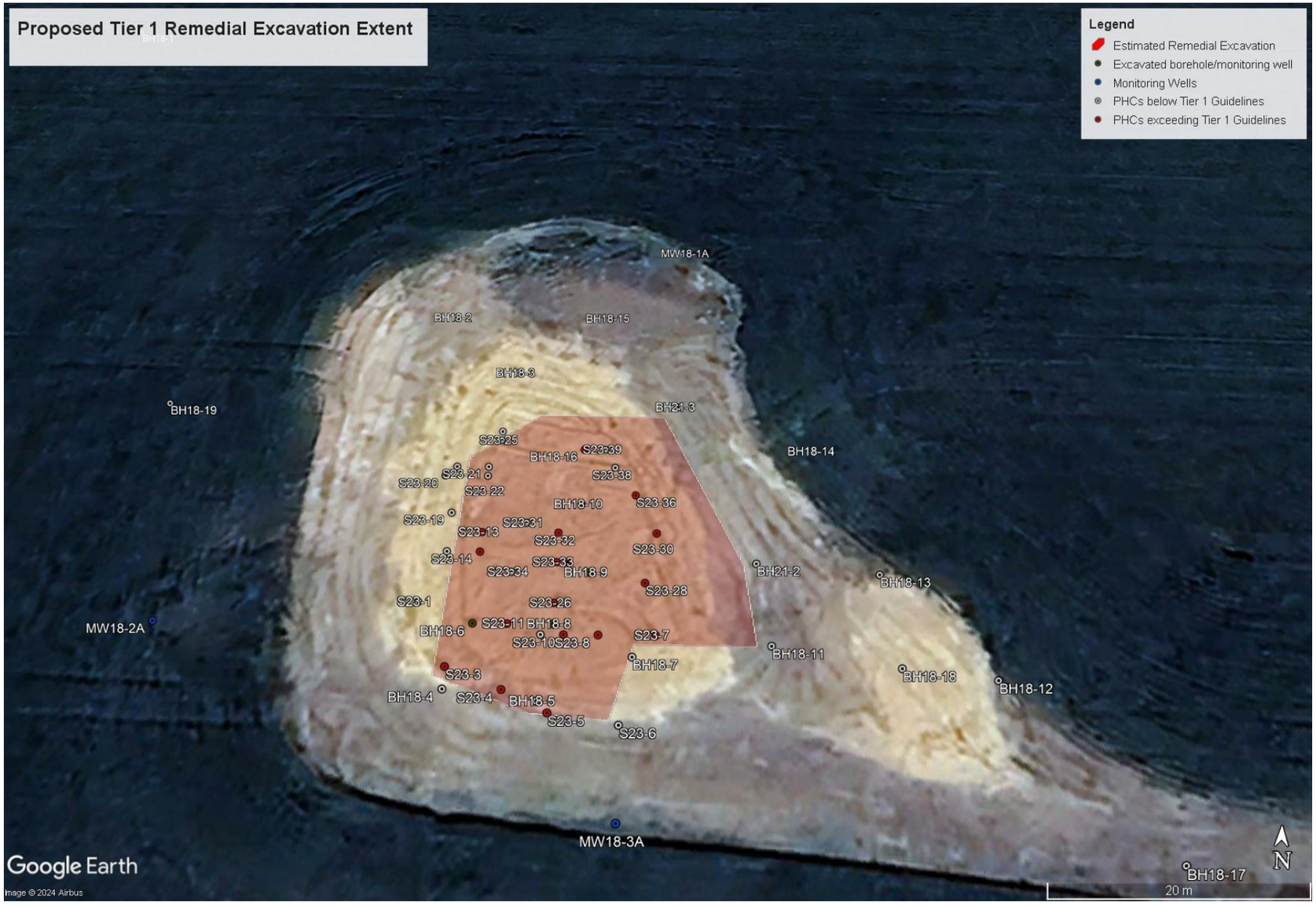


Figure 8. Proposed boundary for a Tier 1 Petroleum Hydrocarbon Remedial Excavation.

CONCLUSION

Based on the findings of my study, the SSRA with Tier 2 adjustments were successful at Site A in reducing human health risks and project costs associated with earthworks. With increasing numbers of inactive wells rising in the Province the Tier 2 strategy provides an effective avenue to closure.

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APPENDICES

APPENDIX A

APPENDIX A PHC SOIL ANALYTICAL DATA

Appendix A

Soil Analytical Results: Petroleum Hydrocarbons (PHCs)

			Petroleum Hydrocarbons (PHCs)															
Sampling Location	Date (dd-mmm-yyyy)	Sample Depth	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	m&p-Xylene (mg/kg)	o-Xylene (mg/kg)	Xylenes (Total) (mg/kg)	Styrene (mg/kg)	PHC F1 (C_6-C_{10}) (mg/kg)	PHC F1 (C_6-C_{10}) - BTEX (mg/kg)	PHC F2 (C_{10}-C_{16}) (mg/kg)	PHC F3 (C_{16}-C_{34}) (mg/kg)	PHC F4 (C_{34}-C_{50+}) (mg/kg)	PHC F4 (C_{34}-C_{50}) (mg/kg)	PHC F4 (C_{34}-C_{50+})-Gravimetric (mg/kg)	PHC Residual Hydrocarbons (C_{50+}) (%)	Reached Baseline at C_{50} (none)
AEP Alberta Tier 1 Agri Fine Surface Soil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**0.68**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 1 Agri Fine Subsoil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**---**	**---**	**420**	**300**	**2600**	**10000**	**10000**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Surface Soil, 2023			**0.33**	**110**	**120**	**---**	**---**	**65**	**---**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Subsoil, 2023			**5**	**1200**	**1900**	**---**	**---**	**140**	**---**	**---**	**630**	**3300**	**---**	**---**	**---**	**---**	**---**	**---**
Background Locations																		
BH18-1	28-Oct-2018	0.0 - 0.15m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.15 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.6 - 1.0m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
MW18-1A	30-Oct-2018	0.15 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	30-Oct-2018	0.6 - 1.0m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
MW18-2A	29-Oct-2018	0.0 - 0.1m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	0.5 - 1.0m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	2.0 - 2.5m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Well Centre																		
BH18-2	28-Oct-2018	0.0 - 0.15m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.3 - 0.6m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.6 - 1.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	2.0 - 2.5m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
BH18-3	28-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.3 - 0.6m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.6 - 1.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
Dehydrator shack/ pipeline riser/ASTs																		
BH18-4	29-Oct-2018	0.0 - 0.2m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	0.2 - 0.6m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	1.0 - 1.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	29-Oct-2018	2.5 - 3.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-5	28-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.6 - 1.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	2.5 - 3.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-6	29-Oct-2018	0.0 - 0.5m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	1.0 - 1.5m	< 0.0050	< 0.014	**0.185**	0.326	< 0.050	0.326	< 0.050	48	47	< 25	< 50	---	< 50	---	---	YES
	29-Oct-2018	2.5 - 3.0m	0.0064	< 0.014	**0.280**	0.455	0.114	0.569	< 0.050	48	47	40	106	---	< 50	---	---	YES
	29-Oct-2018	3.4 - 4.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	---	---	---	---	---	---	---
BH18-7	29-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	1.0 - 1.5m	0.0240	< 0.014	0.024	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-8	28-Oct-2018	1.0 - 1.5m	**32.8**	**280**	**88.2**	272	93.9	**366**	< 2.0	2610	**1840**	101	65	---	< 50	---	---	YES

Appendix A

Soil Analytical Results: Petroleum Hydrocarbons (PHCs)

			Petroleum Hydrocarbons (PHCs)																
Sampling Location	Date (dd-mmm-yyyy)	Sample Depth	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	m&p-Xylene (mg/kg)	o-Xylene (mg/kg)	Xylenes (Total) (mg/kg)	Styrene (mg/kg)	PHC F1 (C_6-C_{10}) (mg/kg)	PHC F1 (C_6-C_{10}) - BTEX (mg/kg)	PHC F2 (C_{10}-C_{16}) (mg/kg)	PHC F3 (C_{16}-C_{34}) (mg/kg)	PHC F4 (C_{34}-C_{50+}) (mg/kg)	PHC F4 (C_{34}-C_{50}) (mg/kg)	PHC F4 (C_{34}-C_{50+})-Gravimetric (mg/kg)	PHC Residual Hydrocarbons (C_{50+}) (%)	Reached Baseline at C_{50} (none)
AEP Alberta Tier 1 Agri Fine Surface Soil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**0.68**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 1 Agri Fine Subsoil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**---**	**---**	**420**	**300**	**2600**	**10000**	**10000**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Surface Soil, 2023			**0.33**	**110**	**120**	**---**	**---**	**65**	**---**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Subsoil, 2023			**5**	**1200**	**1900**	**---**	**---**	**140**	**---**	**---**	**630**	**3300**	**---**	**---**	**---**	**---**	**---**	**---**
	28-Oct-2018	2.5 - 3.0m	**13.5**	**45.5**	**13.9**	47.1	13.9	**61.0**	< 0.40	400	**270**	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	4.1 - 4.5m	8.71	0.587	2.99	10.6	1.61	12.2	< 0.050	75	51	< 25	< 50	---	< 50	---	---	YES
MW18-3A	29-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	1.0 - 1.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	29-Oct-2018	2.0 - 2.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
UST																		
BH18-9	29-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	1.0 - 1.5m	**0.259**	0.19	**61.0**	0.64	< 0.40	0.64	< 0.40	2720	**2660**	66	54	---	< 50	---	---	YES
	29-Oct-2018	2.5 - 3.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-10	28-Oct-2018	0.0 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	28-Oct-2018	0.6 - 1.0m	0.0150	0.020	0.016	0.059	< 0.050	< 0.071	< 0.050	< 10	< 10	65	172	---	93	---	---	YES
	28-Oct-2018	4.0 - 4.2m	0.0522	0.030	0.733	0.167	< 0.050	0.167	< 0.050	< 10	< 10	43	55	---	< 50	---	---	YES
	28-Oct-2018	4.5 - 5.0m	0.418	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	5.5 - 6.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	---	---	---	---	---	---	---
MW21-1A	27-Aug-2021	1.5 - 2.0m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	20	---	13	N/A	---	---
	27-Aug-2021	3.5 - 4.0m	0.747	< 0.05	0.36	---	---	1.32	---	100	100	< 10	10	---	< 10	N/A	---	---
	27-Aug-2021	5.5 - 6.0m	0.194	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	20	---	< 10	N/A	---	---
BH21-2	27-Aug-2021	0.8 - 1.5m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
	27-Aug-2021	4.0 - 4.5m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
	27-Aug-2021	5.5 - 6.0m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
BH21-3	27-Aug-2021	2.5 - 3.0m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	25	---	13	N/A	---	---
	27-Aug-2021	5.0 - 5.5m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
BH21-4	27-Aug-2021	3.5 - 4.0m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	15	---	< 10	N/A	---	---
	27-Aug-2021	4.5 - 5.0m	< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
S23-1	24-Oct-2023	3.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	41	---	30	N/A	---	---
S23-2	24-Oct-2023	5.0m	1.53	< 0.05	0.11	---	---	4.50	---	20	20	< 10	60	---	38	N/A	---	---
S23-3	23-Oct-2023	2.0m	0.014	0.16	**0.077**	---	---	0.32	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
	24-Oct-2023	4.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	56	---	35	N/A	---	---
S23-4	23-Oct-2023	3.0m	< 0.005	< 0.05	0.012	---	---	0.07	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
	24-Oct-2023	5.0m	0.804	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	31	---	20	N/A	---	---
S23-5	23-Oct-2023	3.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	12	---	< 10	N/A	---	---

Appendix A

Soil Analytical Results: Petroleum Hydrocarbons (PHCs)

Sampling Location	Date (dd-mmm-yyyy)	Sample Depth	Petroleum Hydrocarbons (PHCs)																
			Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	m&p-Xylene (mg/kg)	o-Xylene (mg/kg)	Xylenes (Total) (mg/kg)	Styrene (mg/kg)	PHC F1 (C_6-C_{10}) (mg/kg)	PHC F1 (C_6-C_{10}) - BTEX (mg/kg)	PHC F2 (C_{10}-C_{16}) (mg/kg)	PHC F3 (C_{16}-C_{34}) (mg/kg)	PHC F4 (C_{34}-C_{50+}) (mg/kg)	PHC F4 (C_{34}-C_{50}) (mg/kg)	PHC F4 (C_{34}-C_{50+})-Gravimetric (mg/kg)	PHC Residual Hydrocarbons (C_{50+}) (%)	Reached Baseline at C_{50} (none)
AEP Alberta Tier 1 Agri Fine Surface Soil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**0.68**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 1 Agri Fine Subsoil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**---**	**---**	**420**	**300**	**2600**	**10000**	**10000**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Surface Soil, 2023			**0.33**	**110**	**120**	**---**	**---**	**65**	**---**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Subsoil, 2023			**5**	**1200**	**1900**	**---**	**---**	**140**	**---**	**---**	**630**	**3300**	**---**	**---**	**---**	**---**	**---**	**---**
	24-Oct-2023	4.0m	1.08	< 0.05	< 0.010	---	---	0.08	---	< 10	< 10	< 10	< 10	---	16	N/A	---	---
S23-6	23-Oct-2023	2.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
S23-7	24-Oct-2023	4.0m	0.104	< 0.05	0.01	---	---	0.08	---	10	10	< 10	24	---	15	N/A	---	---
S23-8	24-Oct-2023	5.0m	0.445	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	50	---	30	N/A	---	---
S23-9	24-Oct-2023	6.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	45	---	24	N/A	---	---
S23-10	24-Oct-2023	5.5m	0.355	< 0.05	0.04	---	---	0.16	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
S23-11	24-Oct-2023	5.5m	0.075	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	31	---	30	N/A	---	---
S23-12	24-Oct-2023	2.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	37	---	26	N/A	---	---
	24-Oct-2023	4.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	13	N/A	---	---
S23-13	24-Oct-2023	4.0m	< 0.005	< 0.05	0.16	---	---	0.46	---	10	10	< 10	31	---	26	N/A	---	---
S23-14	24-Oct-2023	4.5m	0.055	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	12	---	15	N/A	---	---
S23-19	24-Oct-2023	2.0m	< 0.005	< 0.05	0.01	---	---	< 0.05	---	20	20	10	47	---	33	N/A	---	---
	26-Oct-2023	3.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	20	20	< 10	22	---	15	N/A	---	---
S23-20	26-Oct-2023	1.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	25	---	19	N/A	---	---
	26-Oct-2023	3.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	32	---	20	N/A	---	---
S23-21	26-Oct-2023	3.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	21	---	13	N/A	---	---
S23-22	26-Oct-2023	4.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	< 10	< 10	< 10	< 10	---	< 10	N/A	---	---
S23-24	26-Oct-2023	2.0m	< 0.005	< 0.05	< 0.010	---	---	< 0.05	---	50	50	37	64	---	29	N/A	---	---
S23-26	26-Oct-2023	5.0m	0.060	< 0.05	0.013	---	---	< 0.05	---	< 10	< 10	< 10	20	---	< 10	N/A	---	---
S23-28	26-Oct-2023	3.0m	0.373	< 0.05	1.19	---	---	0.21	---	30	30	< 10	38	---	18	N/A	---	---
S23-30	26-Oct-2023	2.0m	< 0.005	< 0.05	5.57	---	---	0.08	---	70	70	33	70	---	26	N/A	---	---
S23-31	27-Oct-2023	4.0m	< 0.0043	< 0.011	0.013	---	---	0.025	---	20	20	13	38	---	19	N/A	---	---
S23-32	27-Oct-2023	5.0m	1.29	< 0.011	< 0.010	---	---	< 0.024	---	10	< 7.3	< 10	17	---	14	N/A	---	---
S23-33	27-Oct-2023	4.5m	0.0120	< 0.011	0.012	---	---	0.024	---	430	430	15	30	---	15	N/A	---	---
S23-34	27-Oct-2023	3.5m	< 0.0043	< 0.011	0.012	---	---	< 0.024	---	< 7.3	< 7.3	< 10	17	---	13	N/A	---	---
S23-36	27-Oct-2023	2.0m	0.008	< 0.011	1.12	---	---	0.049	---	30	30	---	---	---	---	---	---	---
	27-Oct-2023	2.0m	---	---	---	---	---	---	---	---	---	< 10	24	---	11	N/A	---	---

Appendix A

Soil Analytical Results: Petroleum Hydrocarbons (PHCs)

Sampling Location	Date (dd-mmm-yyyy)	Sample Depth	Petroleum Hydrocarbons (PHCs)																
			Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	m&p-Xylene (mg/kg)	o-Xylene (mg/kg)	Xylenes (Total) (mg/kg)	Styrene (mg/kg)	PHC F1 (C_6-C_{10}) (mg/kg)	PHC F1 (C_6-C_{10}) - BTEX (mg/kg)	PHC F2 (C_{10}-C_{16}) (mg/kg)	PHC F3 (C_{16}-C_{34}) (mg/kg)	PHC F4 (C_{34}-C_{50+}) (mg/kg)	PHC F4 (C_{34}-C_{50}) (mg/kg)	PHC F4 (C_{34}-C_{50+})-Gravimetric (mg/kg)	PHC Residual Hydrocarbons (C_{50+}) (%)	Reached Baseline at C_{50} (none)
AEP Alberta Tier 1 Agri Fine Surface Soil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**0.68**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 1 Agri Fine Subsoil, 2022			**0.046**	**0.52**	**0.073**	**---**	**---**	**0.99**	**---**	**---**	**420**	**300**	**2600**	**10000**	**10000**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Surface Soil, 2023			**0.33**	**110**	**120**	**---**	**---**	**65**	**---**	**---**	**210**	**150**	**1300**	**5600**	**5600**	**---**	**---**	**---**
AEP Alberta Tier 2 Agri Fine Subsoil, 2023			**5**	**1200**	**1900**	**---**	**---**	**140**	**---**	**---**	**630**	**3300**	**---**	**---**	**---**	**---**	**---**	**---**
S23-38	28-Oct-2023	2.0m	< 0.0043	< 0.011	0.027	---	---	0.027	---	20	20	15	36	---	13	N/A	---	---
	28-Oct-2023	4.0m	< 0.0043	< 0.011	0.013	---	---	< 0.024	---	10	10	< 10	< 10	---	< 10	N/A	---	---
S23-39	28-Oct-2023	2.0m	0.009	< 0.011	0.012	---	---	< 0.024	---	10	10	< 10	13	---	< 10	N/A	---	---
	28-Oct-2023	3.0m	< 0.0043	< 0.011	0.013	---	---	< 0.024	---	20	20	< 10	41	---	15	N/A	---	---
400 bbl AST within berm																		
BH18-11	30-Oct-2018	1.0 - 1.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	30-Oct-2018	2.5 - 3.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-12	29-Oct-2018	0.3 - 0.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-13	29-Oct-2018	0.0 - 0.15m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	29-Oct-2018	2.0 - 2.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-14	29-Oct-2018	0.4 - 0.7m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
BH18-18	29-Oct-2018	1.5 - 2.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	29-Oct-2018	3.0 - 3.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
Potential Drilling Sump																		
BH18-15	28-Oct-2018	1.0 - 1.5m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	2.5 - 3.0m	< 0.0050	< 0.014	< 0.015	< 0.050	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
BH18-16	28-Oct-2018	2.2 - 3.0m	0.0107	0.018	0.047	0.068	< 0.050	< 0.071	< 0.050	35	35	< 25	< 50	---	< 50	---	---	YES
	28-Oct-2018	4.1 - 4.5m	0.0872	0.120	0.027	0.051	< 0.050	< 0.071	< 0.050	< 10	< 10	< 25	< 50	---	< 50	---	---	YES
Access Road																		
BH18-17	30-Oct-2018	0.1 - 0.3m	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
HA22-01	24-Aug-2022	0.0 - 0.15m	< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	< 25	< 50	< 100	< 100	---	< 5.0	---
(Duplicate)	24-Aug-2022	0.0 - 0.15m	< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	< 25	< 50	< 100	< 100	---	< 5.0	---
HA22-02	24-Aug-2022	0.0 - 0.1m	< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	< 25	< 50	< 100	< 100	---	< 5.0	---
HA22-03	24-Aug-2022	0.0 - 0.2m	< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	< 25	< 50	< 100	< 100	---	< 5.0	---
HA22-04	24-Aug-2022	0.0 - 0.15m	< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	< 25	< 50	< 100	< 100	---	< 5.0	---
QAQC																		
Trip Blank	27-Aug-2021		< 0.005	< 0.05	< 0.01	---	---	< 0.05	---	< 10	< 10	---	---	---	---	---	---	---
	24-Aug-2022		< 0.005	< 0.02	< 0.005	---	---	< 0.03	---	< 10	< 10	---	---	---	---	---	---	---

Appendix A

Soil Analytical Results: Petroleum Hydrocarbons (PHCs)

Sampling Location	Date (dd-mmm-yyyy)	Sample Depth	Petroleum Hydrocarbons (PHCs)															
			Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	m&p-Xylene (mg/kg)	o-Xylene (mg/kg)	Xylenes (Total) (mg/kg)	Styrene (mg/kg)	PHC F1 (C_6-C_{10}) (mg/kg)	PHC F1 (C_6-C_{10}) - BTEX (mg/kg)	PHC F2 (C_{10}-C_{16}) (mg/kg)	PHC F3 (C_{16}-C_{34}) (mg/kg)	PHC F4 (C_{34}-C_{50+}) (mg/kg)	PHC F4 (C_{34}-C_{50}) (mg/kg)	PHC F4 (C_{34}-C_{50+})-Gravimetric (mg/kg)	PHC Residual Hydrocarbons (C_{50+}) (%)	Reached Baseline at C_{50} (none)
AEP Alberta Tier 1 Agri Fine Surface Soil, 2022			0.046	0.52	0.073	---	---	0.99	0.68	---	210	150	1300	5600	5600	---	---	---
AEP Alberta Tier 1 Agri Fine Subsoil, 2022			0.046	0.52	0.073	---	---	0.99	---	---	420	300	2600	10000	10000	---	---	---
AEP Alberta Tier 2 Agri Fine Surface Soil, 2023			0.33	110	120	---	---	65	---	---	210	150	1300	5600	5600	---	---	---
AEP Alberta Tier 2 Agri Fine Subsoil, 2023			5	1200	1900	---	---	140	---	---	630	3300	---	---	---	---	---	---

NOTES:

1. --- in guideline row(s) denotes no criteria for that parameter.
2. --- in detail data row(s) denotes parameter not analyzed.
3. Highlighting indicates non-detect parameters above applied guideline/criteria.
4. Highlighting indicates parameters at applied guideline/criteria.
5. Denotes values exceeding
   (AEP Alberta Tier 1, August 2022, Agricultural Land Use Criteria, Fine-Grained Surface Soil)
6. Denotes values exceeding
   (AEP Alberta Tier 1, August 2022, Agricultural Land Use Criteria, Fine-Grained Subsoil)

PHC F1 (C_6-C_{10}) - BTEX:
Includes the ecological direct contact pathway which can be excluded below 3 mbgs

PHC F2 (C_{10}-C_{16}):
Includes the ecological direct contact pathway which can be excluded below 3 mbgs

PHC F3 (C_{16}-C_{34}):
Includes the ecological direct contact pathway which can be excluded below 3 mbgs

PHC F4 (C_{34}-C_{50}):
Includes the ecological direct contact pathway which can be excluded below 3 mbgs

PHC F4 (C_{34}-C_{50+}):
Includes the ecological direct contact pathway which can be excluded below 3 mbgs

APPENDIX B

APPENDIX B THREE-PHASE PARITION MODEL

EQUATIONS

Three-Phase Partioning Equations adopted from Federal Contaminated Site Risk Assessment in Canada, Part VII: Guidance For Soil Vapour Intrusion Assessment At Contaminated Sites (Health Canada, 2010).

2. Soil Contamination Source (Not Recommended)

If $C_{soil,i} < C_{sat,soil,i}$ then $C_{v,i} = UCF_2 * C_{soil,i} * H' * \rho_b / (\theta_w + K_{oc}*f_{oc}* \rho_b + H'*\theta_a)$

If $C_{soil,i} >= C_{sat,soil,i}$ then $C_{v,i} = \max [UCF_2 * C_{soil,i} * H' * \rho_b / (\theta_w + K_{oc}*f_{oc}* \rho_b + H'*\theta_a),\ UCF_1 * MW_i * X_i * P_i / RT]$

$C_{sat,soil,i} = S^* (\theta_w + K_{oc}*f_{oc}* \rho_b + H'*\theta_a)/ \rho_b$

Parameter	Default
$C_{w,i}$ = Ground water concentration (mg/L)	Measured site specific
X_i = Mole fraction (no units)†	Estimated from chemical data
S_i = Pure chemical aqueous solubility (mg/L)	Chemical specific
$C_{v,i}$ = Soil vapour concentration (mg/m³)	Calculated
H' = Dimensionless Henry's Law constant	Chemical specific
UCF_1 = Unit conversion factor	1,000 mg/g
UCF_2 = Unit conversion factor	1,000 L/m^3
MW_i = Molecular weight (g/mole)	Chemical specific
P = Pure chemical vapour pressure (atm)	Chemical specific
R = Gas constant (m^3-atm/K-mole)	8.21E-05
T = Absolute temperature (K, 273°C + T(°C))	Estimated
$C_{soil,i}$ = Total soil concentration (mg/kg)	Measured site specific
$C_{sat,soil,i}$ = Soil saturation concentration (mg/kg)	Calculated
ρ_b = Dry bulk density (k /L)	1.6
θ = Total porosity (dimensionless)	0.375 (coarse-grained soil)
	0.399 (fine-grained soil)
θ_w = Water-filled porosity (dimensionless)	0.054 (coarse-grained soil)
	.148 (fine-grained soil)
K_{oc} = Organic carbon-water partitioning coefficient (g/kg-OC per mg/L-water)	Chemical specific
f_{oc} = Fraction organic carbon (dimensionless)	0.006 (recommend measure)
θ_a = Air-filled porosity (dimensionless)	$\theta - \theta_w$

Note: For chemicals that are solids at room temperature, the sub-cooled liquid solubility should be used in place of the solid solubility. Calculations for temperature corrected vapour pressure and Henry's constant are shown in Exhibit 3.

† See Appendix A for instructions on how to calculate the mole fraction of petroleum solutions.

(A8)

$$X_i = C_{soil,i} / TPH * MW_{TPH} / MW_i$$

where $C_{i,soil}$ is the concentration of the individual compound in soil (mg/kg), TPH is the total petroleum hydrocarbon concentration in soil (mg/kg), MW_{TPH} is the average molecular weight of the petroleum hydrocarbon, and MW_i is the molecular weight of the compound.

Appendix B - Three-Phase Partition Model - Soil Vapor Concentration Based on Soil Concentration

Input Parameters	Symbol	Units	Benzene Surface Soil	Benzene Subsurface Soil
Soil Exposure Point Concentration (EPC)	$C_{soil,i}$	mg/kg	0.02	1.53
Solubility	S'	mg/L	1.78E+03	1.78E+03
Total Porosity	Θ	unitless	0.399	0.399
Water-filled Porosity	Θw	unitless	0.269	0.269
Air-filled Porosity	Θa	unitless	3.50E-02	3.50E-02
Organic Carbon-water Partitioning Coefficient	K_{oc}	L/kg	81.00	81.00
Fraction organic carbon	f_{oc}	unitless	0.021	0.021
Dry Bulk Density	p_b	kg/L	1.88	1.88
Henry's Law Constant	H'	unitless	2.25E-01	2.25E-01
Soil saturation concentration	$C_{sat,soil,i}$	mg/kg	**3290**	**3290**
Unit Conversion Factor	UCF1	mg/g	1000	1000
Unit Conversion Factor	UCF2	L/m^3	1000	1000
Molecular weight	MW_i	g/mole	7.80E+01	7.80E+01
Mole Fraction	X_i	unitless	-	-
Pure chemical vapour pressure	P_i	atm	6.20E-02	6.20E-02
Gas Constant	R	m^3-atm/K-mole	8.21E-05	8.21E-05
Absolute Temperature	T	K	2.98E+02	2.98E+02
Soil Vapour Concentration	$C_{v,i}$	mg/m^3	2.92E+00	1.86E+02

APPENDIX C

APPENDIX C INDOOR AIR-ATTENUATION FACTORS

Subsoil							
	L_T	D_a	D_{eff}	D_{crack}	Q_B	Qsoil	α
Benzene	30	8.80E-02	1.34E-05	0.017988	75031.25	0.914382	1.017E-05
Benzene	100	8.80E-02	1.34E-05	0.017988	75031.25	0.914382	4.099E-06
Surface Soil							
	L_T	D_a	D_{eff}	D_{crack}	Q_B	Qsoil	α
Benzene	30	8.80E-02	1.34E-05	0.017988	75031.25	0.914382	1.017E-05

Default Parameters (fine-grained soil basement scenario)	
θ_t	0.304
θ_a	0.035
L_B	1225
W_B	1225
H_B	360
ACH	0.5
ΔP	40
k_v	0.000000001
X_{crack}	4900
Z_{crack}	244
r_{crack}	0.202959184
μ	0.000173
AB	2.7E+06
L_{crack}	11.25
A_{crack}	994.5

Notes:

Equations are from Alberta Tier 1 Soil and Remediation Guidelines (AEP 2019), originally from Johnson, P.C. and R.A. Ettinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. Environ. Sci. Tech., 25: 1445-1452.

Grey highlighting means values sourced from Alberta Tier 1 Soil and Groundwater Remediation Guidelines 2019.

All other values were calculated based on the provided equations. All units as described below.

$$\alpha = \frac{\left(\frac{D_T^{eff} A_B}{Q_B L_T}\right) exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right)}{exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_B L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]}$$

Where:

- α = contaminant concentration in building ÷ contaminant concentration in soil vapours (unitless)
- D_T^{eff} = effective porous media diffusion coefficient (cm^2/s; calculated below);
- A_B = building area (cm^2);
- Q_B = building ventilation rate (cm^3/s; calculated below);
- L_T = distance from contaminant source to foundation (cm);
- Q_{soil} = volumetric flow rate of soil gas into the building (cm^3/s; calculated below);
- L_{crack} = thickness of the foundation (cm);
- D_{crack} = effective vapour diffusion coefficient through the crack (cm^2/s; calculated below); and,
- A_{crack} = area of cracks through which contaminant vapours enter the building (cm^2).

Calculation of D_T^{eff}:

$$D_T^{eff} \approx D_a \times \left(\frac{\theta_a^{10/3}}{\theta_t^2}\right)$$

Where:

- D_T^{eff} = overall effective porous media diffusion coefficient based on vapour-phase concentrations for the region between the source and foundation (cm^2/s);
- D_a = diffusion coefficient in air (cm^2/s);
- θ_a = soil vapour-filled porosity (dimensionless); and,
- θ_t = soil total porosity (dimensionless).

Calculation of D_{crack}:

D_{crack} is calculated in exactly the same way as D_T^{eff}, with the exception that the assumption is made that the soil material in the cracks is dry (CCME, 2006a), and accordingly, the soil air filled porosity is the same as the soil total porosity, and the equation becomes:

$$D_{crack} \approx D_a \times \left(\frac{\theta_t^{10/3}}{\theta_t^2} \right)$$

Where:

D_{crack}	=	effective porous media diffusion coefficient in floor cracks (cm^2/s);
D_a	=	diffusion coefficient in air (cm^2/s);
θ_t	=	total porosity (dimensionless).

Calculation of Q_B:

$$Q_B = \frac{L_B W_B H_B ACH}{3{,}600}$$

Where:

Q_B	=	building ventilation rate (cm^3/s);
L_B	=	building length (cm);
W_B	=	building width (cm);
H_B	=	building height (cm);
ACH	=	air exchanges per hour (h^{-1}); and,
3,600	=	conversion factor from hours to seconds.

Calculation of Q_{soil}:

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \, ln\left[\frac{2Z_{crack}}{r_{crack}} \right]}$$

Where

Q_{soil}	=	volumetric flow rate of soil gas into the building (cm^3/s);
ΔP	=	pressure differential ($g/cm \cdot s^2$);
k_v	=	soil vapour permeability to vapour flow (cm^2);
X_{crack}	=	length of idealized cylinder (cm);
μ	=	vapour viscosity (0.000173 g/cm·s; CCME, 2008a);
Z_{crack}	=	distance below grade to idealized cylinder (cm); and,
r_{crack}	=	radius of idealized cylinder (cm; calculated as A_{crack}/X_{crack}).